AD-A172 151 FACILITATION OF SCIENTIFIC CONCEPT LEARNING BY INTERPRETATION PROCEDURES AND DIAGNOSIS(U) CALIFORNIA UNIV BERKELEY SCHOOL OF EDUCATION P LABUDDE ET AL. AUG 86 CES-4 N00014-83-K-0598 1/1

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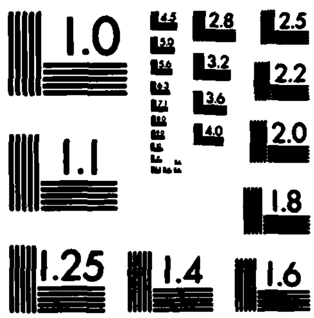

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August 1986 Report No. CES-4

AD-A172 151

Facilitation of Scientific Concept Learning by Interpretation Procedures and Diagnosis

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The work reported here was supported by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under contract No. N00014-83-K-0598, contract authority No. NR 154-522. Additional support was provided by the National Science Foundation through grant No. MDR-8550332.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A172 151

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) CES-4	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION University of California 6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION Personnel and Training Research Programs Office of Naval Research (Code 1142 PT)
6c. ADDRESS *(City, State, and ZIP Code)* Berkeley, California 94720	7b. ADDRESS *(City, State, and ZIP Code)* 800 North Quincy Street Arlington, VA 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-83-K-0598
8c. ADDRESS *(City, State, and ZIP Code)*	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61153N PROJECT NO.: RR04206 TASK NO.: RR0420601 WORK UNIT ACCESSION NO.:

11. TITLE *(Include Security Classification)*
Facilitation of Scientific Concept Learning by Interpretation Procedures and Diagnosis.
(Unclassified)

12. PERSONAL AUTHOR(S)
Peter Labudde, Frederick Reif, Lisa Quinn

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Technical	FROM 86/1 TO 86/8	1986, August	19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Concepts; science; learning; instruction

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Susan Chipman	22b. TELEPHONE *(Include Area Code)* 202/696-4318 22c. OFFICE SYMBOL ONR 1142PT

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Facilitation of Scientific Concept Learning by Interpretation Procedures and Diagnosis

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Abstract

Students' difficulties in learning and applying scientific concepts are often caused by knowledge that is fragmented and incorrectly interpreted. To remedy such difficulties, we propose an explicit instructional method that teaches a coherent procedure for interpreting a scientific concept, and that induces students to use this procedure for explicitly diagnosing and correcting defects in their preexisting knowledge. To test this method, the concept "acceleration" was taught to individual students under conditions where they could be observed in detail and tape-recorded during the entire learning process. As a result of such instruction, students revised their highly deficient previous knowledge about acceleration and were able to interpret this concept almost flawlessly across a diverse set of problems.

Introduction

The learning of scientific concepts, particularly in the physical sciences, presents severe difficulties for many students. Recent research indicates that such difficulties are due to: (a) a knowledge base that is fragmented, incoherent, and prone to misconceptions (diSessa, in press; Green, McClosky & Caramazza 1985; Halloun & Hestenes 1985a, 1985b; McDermott 1984; Reif 1986); (b) unsystematic or inefficient search and retrieval processes (Larkin 1981; Larkin, McDermott, Simon & Simon 1980); (c) an inability to apply knowledge appropriately after it has been retrieved (Reif 1986); and (d) failure to distinguish between concepts and reasoning modes used in science versus those used in everyday life (diSessa 1985; Reif 1986; Solomon 1984).

Common ways of teaching scientific concepts contribute to students' conceptual difficulties. First, a scientific concept is usually introduced by verbal or mathematical definitions that describe the concept by some characterizing features, but do not specify the actual procedures necessary to identify or to construct the concept. Hence students must infer such procedural knowledge themselves and are often left with interpretation processes that are inadequate or faulty. Second, concepts are often introduced without making explicit connections with students' previous conceptions, and without having students adequately compare and contrast unfamiliar scientific concepts with preexisting notions. Yet, an adequate comparison of new and preexisting knowledge appears to be necessary for restructuring knowledge to achieve the integration and "accommodation" needed for effective learning (Piaget 1970).

The preceding student difficulties and inadequacies of current teaching methods suggest the following instructional principles for teaching scientific concepts more effectively: (a) Procedural knowledge for interpreting a scientific concept should be explicitly taught together with descriptive knowledge about the concept. (b) New knowledge should be taught in a coherent form so that it can be easily remembered, retrieved, and contrasted with preexisting fragmented knowledge. (c) Instruction should be explicit to facilitate knowledge integration, as well as to minimize student errors caused by incorrect inductions from vague and incomplete information. (d) New knowledge should be explicitly contrasted with prior knowledge in order to remove inconsistencies, to ensure the coherence of the student's new knowledge, and to minimize interference from conflicting prior knowledge.

These instructional principles can be viewed as theoretical hypotheses that can be translated into specific methods for teaching scientific concepts. By implementing these methods under controlled conditions, one can then assess the efficacy of these methods and of the underlying principles upon which they are based.

The remainder of this paper discusses a detailed investigation where these instructional principles were tested by implementing them to teach the physics concept "acceleration". The instruction involved primarily teaching an explicit procedure specifying the concept, and then providing practice whereby students applied this procedure and compared the results with their previous knowledge. We hypothesized that such instruction would lead to reliably accurate concept interpretations by the students, would minimize the effects of interference due to their prior notions, and would enable them to detect, to diagnose, and to correct concept-interpretation errors committed by themselves or by others.

In the following pages we first outline the procedural specification of the concept acceleration. Next we describe the experimental methods for investigating the teaching of this concept according to our proposed principles. Then we discuss the resulting data regarding students' knowledge and

performance, both before the instructional intervention and afterwards. Finally, we summarize the main conclusions and suggest some questions worthy of further investigation.

Acceleration and its Procedural Specification

As subject matter for our investigation, we chose the concept of acceleration. This concept is not only very important in physics and typical of concepts in other quantitative sciences, but is also difficult to learn (Trowbridge & McDermott 1981; Halloun & Hestenes 1985b).

The descriptive definition of acceleration can be found summarized in any textbook by the formula **a** = d**v**/dt, where **a** is the acceleration vector, **v** the velocity vector, and t the time. A less precise descriptive definition is provided by the corresponding verbal statement that "acceleration is the rate of change of velocity with time".

The procedural specification of acceleration is outlined and illustrated in Figure 1 in the form presented to students in our experiment. It includes the following four major steps: (1) Identify the velocity **v** of the particle at the time t of interest. (2) Identify its velocity **v'** at a slightly later time t'. (3) Find the change of velocity Δ**v** = **v'**-**v** by vector subtraction of the two velocities. (4) Divide Δ**v** by the elapsed time Δt to find the ratio Δ**v**/Δt. The result is called the "acceleration" **a**, if the time interval Δt is sufficiently small. [A more detailed description of the procedural specification, including the limiting process when Δt approaches zero, can be found in Reif (1985).]

*** Insert Figure 1 about here ***

Since this procedure specifies explicitly how the acceleration can be determined in all cases, it provides highly coherent knowledge about this concept. The implementation of the steps in this procedure presupposes, however, adequate prerequisite knowledge about the descriptive definition of acceleration, as well as about velocity, vectors, and vector subtraction.

Experimental Method

Overview

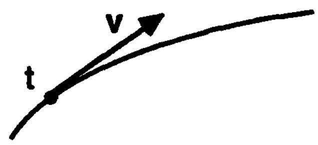
Six students, enrolled in an introductory physics course, were individually questioned and taught, while being tape-recorded in two sessions, each lasting about 45 minutes (see Figure 2). The first session began with a pretest which assessed how students interpreted the concept acceleration before instruction, i.e., what kind of knowledge they invoked, how they applied it, and what errors they made. The second part of this session was then used to teach students the procedural specification of acceleration.

*** Insert Figure 2 about here ***

The second session consisted of three distinct phases. The first was designed to assess the extent to which application of the procedural specification helped students to detect and diagnose their own

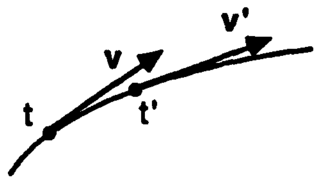
(1) Original velocity (v)

Draw the vector v at the time of interest.



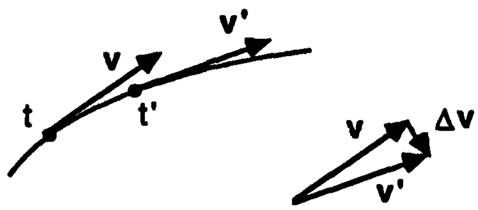
(2) New velocity (v')

Draw the vector v' at a slightly later time.



(3) Change of velocity (Δv)

Draw a separate vector diagram so that the arrow tails of v and v' coincide. Construct the vector Δv which is the vector drawn from the head of the original velocity v to the head of the new velocity v'.



(4) Acceleration (a)

Divide the vector Δv by Δt to obtain a new vector Δv/Δt having the same direction as Δv (but different magnitude and units). If the time interval Δt is sufficiently small, this vector is the acceleration a. Draw the vector a at the time of interest.

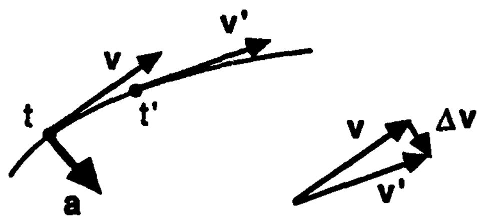


Figure 1. Procedural specification of acceleration.

Session 1	**Pretest** Finding acceleration (by any method)
	Teaching of procedural specification
Session 2	**Diagnosis of own mistakes** (by procedural specification)
	Diagnosis of others' mistakes (by procedural specification)
	Posttest Finding acceleration and diagnosing others' mistakes (by any method)

Figure 2. Experimental design.

previous mistakes in the pretest. The second phase provided practice in detecting and diagnosing others' concept-interpretation mistakes. The third phase was a posttest aiming to assess students' final knowledge, concept-interpretation processes, and abilities to detect and diagnose mistakes in concept interpretation. The following sections describe each experimental phase in greater detail.

Pretest

The pretest, lasting about 10-15 minutes, used a questionnaire consisting of five questions. In each question a specific situation was presented, using both prose and a diagram, and was followed by two subquestions. The first of these asked whether the acceleration was zero or not; the second asked the student to draw an arrow indicating the direction of acceleration (if it was not zero). The five problems were designed to present, roughly in order of increasing complexity, cases of motion along the following kinds of paths: straight line with increasing speed, curved path with constant speed, straight line with decreasing speed, curved path with increasing speed, and straight path with instantaneously zero speed. The questions differed considerably in their surface structures: a car on a road (in two questions), a ball tossed vertically upward, a swinging pendulum, a spring oscillating vertically up and down. A detailed description of all questions can be found in the Appendix (questions 1.1-1.5).

The students worked through the questionnaire twice during the pretest. The first pass was intended to elucidate a student's spontaneous thinking with minimal intrusion by the experimenter (who intervened only if the student misunderstood a given situation or forgot to think aloud By contrast, the second pass was intended to probe the student's underlying reasoning more deeply. To this end, the experimenter asked for further explanations, but did not comment on the merit of the student's responses.

Teaching of procedural specification

The teaching phase, lasting 20-25 minutes, used a specially designed summary sheet. This sheet first stated a brief descriptive definition of acceleration and then outlined the procedural specification of this concept. Figure 1 indicates how the four steps of the procedural specification were presented and exemplified in the case of a particle moving with constant speed along a curved path.

The summary sheet was used as the basis for the entire instruction. The experimenter first asked the student to read through each step of the specification procedure. Then he discussed each step briefly to ensure the student's comprehension. For example, after the first step, he asked the student to explain the difference between speed and velocity, and also to describe the significance of the length of the arrow representing the velocity vector. If the student was unable to give a correct answer, the experimenter would explain. Furthermore, the experimenter pointed out how each step of the procedure was related to the descriptive definition of the acceleration. Finally, the experimenter answered any question asked by the student, but avoided making comments beyond the scope of the question.

A second sheet was designed to provide structured practice in applying the procedural specification. This practice sheet used prose descriptions and diagrams to present examples of the following types of situations: a particle moving with increasing speed along a straight line, a particle moving with decreasing speed along a straight line, and a particle moving with constant speed along an ellipse. Students were asked to answer the questions by implementing the procedural specification step-by-step, using the given diagram of the situation. If a student applied the procedure improperly, the experimenter corrected the student if hints alone proved to be ineffective.

Diagnosis and correction of own mistakes

A break of 2-8 days occurred between the teaching of the procedure and this next phase of the experiment at the beginning of the second session. (The length of the break appeared to have no differential effects across students.) To refresh a student's memory after the break, he or she was first given a few minutes to review the previous instructional materials. These materials then remained accessible to the student for the entire duration (20-25 minutes) of this phase of the experiment.

After the review of the instructional materials, the student was shown the original pretest with his or her previous answers. For each question on this test, the student was then asked to find the correct answer by using the procedural specification of acceleration. (Any mistakes in the student's implementation of the procedure were corrected by the experimenter, once again only if hints proved to be ineffective.) Next the student was requested to determine if there was a discrepancy between the answer obtained by the procedural specification and the student's own previous answer on the pretest. If so, the student was asked to perform a diagnosis by identifying the reasons responsible for his or her previous mistakes. (The experimenter did not intervene during this diagnosis task.) Finally, the student was asked to formulate any warnings that might help prevent similar mistakes in the future.

A minor variation in the experiment, tried with some of the students, involved giving the student a special "checklist" containing brief descriptions of six common mistakes about acceleration (e.g. confusing the lay and scientific meaning of acceleration, confusing velocity and acceleration, or confusing the actual acceleration with that due to gravity alone). The purpose of this list was to help students identify underlying reasons for concept-interpretation mistakes. This checklist was given to 4 out of the 6 students, with only minimal special instruction or explanations. The students were merely told that the checklist mentioned some common mistakes involving acceleration, and that it might be helpful in diagnosing errors detected by the students.

Diagnosis and correction of others' mistakes

This phase of the experiment, lasting only 5-10 minutes, aimed to give students practice in detecting, diagnosing, and correcting another person's concept-interpretation mistakes. Such practice served as preparation for similar diagnostic tasks used in the final posttest.

The questionnaire used in this phase of the experiment contained only two questions (detailed in the Appendix, questions 2.1 and 2.2). Each of these questions was similar to those used in the pretest, i.e., it described a specific situation and then asked for the magnitude of the acceleration (whether zero or not) and its direction. However, each question included also an answer allegedly given by some other person. (These "hypothetical" answers were actually designed to reflect common misconceptions and to test the students' diagnostic capabilities.) The hypothetical answers included with these two questions were both wrong.

For each of these questions the student was asked to use the procedural specification to do the following: (a) to determine whether the given answer was correct or wrong; (b) if wrong, to identify probable reasons accounting for the mistake; and (c) to give the correct answer.

Any mistakes in implementing the procedural specification were again corrected by the experimenter if hints alone were insufficient. All students were allowed to refer to the instructional materials from the previous teaching sequence. The four students, who had access to the checklist in the previous phase, could also use it during the present phase.

Posttest

The posttest, lasting 10-15 minutes, contained five questions identical in structure to the two questions of the previous phase (see the Appendix, questions 3.1-3.5). The given hypothetical answers were wrong in 4 out of the 5 questions, again in ways reflecting common mistakes or misconceptions. Only the answer given for the second question was correct

In all other respects the questions in this posttest were fundamentally similar to those in the pretest. In particular, the questions dealt with the same five types of cases: three straight-line cases with increasing, decreasing, and instantaneously zero speed, respectively; and two curved-path cases with constant and changing speed, respectively. However, the same surface structures in the pretest corresponded to different cases in the posttest. For example, in the pretest the ball tossed upward illustrated the case of decreasing speed along a straight line; but in the posttest the motion of this ball illustrated the case of instantaneously zero speed. The posttest differed from the pretest primarily in its inclusion of given hypothetical answers.

All students were requested to answer the questions by using whatever method was simplest for them, i.e. with or without the procedural specification. Instructional materials, checklist, and previous questionnaires were not accessible during the posttest. The experimenter intervened only to request clarification of an incomplete explanation.

Subjects and protocol analysis

The six subjects used in the experiment were unpaid volunteers enrolled as students in the first semester of an introductory calculus-based physics course at the University of California at Berkeley. This course, intended for physical scientists and engineers, devotes its first semester to the study of mechanics. The experiment was conducted in the second half of the semester, i.e. several weeks after the students had learned and repeatedly applied the acceleration concept in the course. Grades received on the midterm examination indicated that four of the students ranked near the middle of the class, one in the top quarter, and one in the bottom quarter.

Data were collected in sessions where individual students answered the questionnaires, or were taught the procedural interpretation, while being asked to talk aloud about their thinking. Except in the teaching phase, the experimenter intervened minimally. All sessions were audio-recorded and afterwards transcribed into protocols. To maximize objectivity and ease of analysis, protocols were encoded according to an explicit standardized procedure, as recommended by Ericsson and Simon (1984). To minimize subjective interpretations, two of us separately encoded and interpreted half of the protocols. Since a comparison of these encodings and analyses showed no major differences, the other half of the protocols were encoded by only one person. Our final analysis of the data involved group discussions about the interpretation of the individual protocols and of the aggregate data.

Students' Initial State: Data and Discussion

Accuracy of answers

Across students, only 40% of the pretest questions were answered completely correctly. Since each of the 6 students answered 5 questions, there were altogether 30 answers. Of these, 22 reflected a

correct specification of the magnitude of acceleration (whether zero or not), and only 12 reflected a correct specification of the direction of acceleration.

Nearly all students had difficulties with the same three questions. In question 1.2 (car moving with constant speed along a curve), three students answered incorrectly "zero acceleration" and one claimed wrongly that the acceleration, while non-zero, was directed along the velocity. In question 1.4 (horizontal pendulum) all students answered "non-zero acceleration", but indicated a wrong direction: four students answered "straight down", one "toward the center", and one "curved along the arc". In question 1.5 (oscillating spring at the lowest point), five students claimed incorrectly that the acceleration is zero; the one student who claimed otherwise was unable to identify its direction.

Note that only 40% of students' answers were correct, although all our questions required only qualitative answers, and although all students had used acceleration for several weeks in their current physics class. In particular, most students were unable to apply the acceleration concept properly in situations deviating from the standard cases ordinarily discussed in physics courses (cases dealing with motion along a straight line or with circular motion with constant speed). Students had greater difficulty in identifying the direction of the acceleration than in deciding whether its magnitude was zero or not. Although the students' poor performance is disillusioning, it is consistent with data reported by other investigators (Halloun & Hestenes 1985b; Trowbridge & McDermott 1981).

Students' conceptual knowledge

Through detailed examination of students' verbal statements, we made inferences about the nature of students' conceptual knowledge about acceleration. For example, from a student's statement that "the car is moving with increasing speed, so it has an acceleration", we inferred the underlying knowledge that "if the speed is increasing, the acceleration is non-zero". Similarly, from the statement "the particle is moving with constant speed along a circle in a counterclockwise sense, so its acceleration is towards the center", we inferred the knowledge that "if an object moves with constant speed along a circle, the acceleration is directed toward the center".

Students appear to retrieve such "knowledge elements" directly from memory and then apply them with little additional processing. These knowledge elements have generality transcending specific situations or surface features (e.g., they deal with objects moving along certain kinds of paths, rather than with cars moving along roads). However, the extent of their generality can vary and is typically much less than that of a general definition of the concept.

The underlying knowledge elements reflected by students' statements can be classified as being either sound or deficient. "Sound elements" are those which are not only correct according to physics, but which were also applied properly and with confidence. "Deficient elements" can be subdivided into three types: those specifying incorrect physics, those which were incorrectly applied, and those about which the student was uncertain. (Such deficient elements must be remedied by appropriate teaching interventions.)

Across students, we identified a set of 27 <u>distinct</u> knowledge elements, of which 7 were sound and 20 deficient. Altogether, we could identify a total of 21 sound elements and 33 deficient elements, including <u>common</u> elements used by several students. Each student invoked, on average, about 10 different knowledge elements (ranging from 8 to 15). At least half of these were deficient (80% of them were deficient in the case of one student). Of the 33 deficient knowledge elements, 20 were used directly as the basis for an answer. The other 13 were invoked, but then not used.

Examples of sound knowledge elements include the following: "if the speed is increasing or decreasing, the acceleration is non-zero" (invoked by all students); "if the speed is increasing along a straight line, the acceleration is directed along the velocity" (invoked by four students).

Examples of deficient knowledge elements include the following: "if the velocity is zero, the acceleration is zero" (5 students); "if an object moves with constant speed, the acceleration is zero" (2 students). Some of the deficient knowledge elements appear to derive from the everyday notion of acceleration which describes merely increases of speed. Other deficient knowledge elements, although correct, either could not be interpreted in particular situations, or could not be related to a more general definition of acceleration, or were applied without heeding restrictive applicability conditions. The following three quotes illustrate some of these characteristics of deficient knowledge elements.

Quote 1 (Student 4)

(Question 1.5, spring at lowest point: Knowledge element with wrong physics content.)

"Since the speed is instantaneously zero at the lowest point A, then the acceleration is zero."

Quote 2 (Student 6)

(Question 1.4, horizontal pendulum: Wrong application of knowledge element "if gravity is acting, then the acceleration is downward".)

"Since, hm, the pendulum is released from A (the highest point of the arc) and going downward in, hm, this, hm, circular motion, it's going, well there's a gravitational pull, so it's going down, and gravitation itself is some kind of acceleration and therefore, hm, the acceleration of the pendulum bob is not zero and it's going downward."

Quote 3 (Student 5)

(Question 1.2, car moving with constant speed along a curve: Uncertainty about knowledge element "if an object moves with constant speed along a curve, the acceleration is directed inward toward the center".)

"The car, since it is at a constant speed, it doesn't have an acceleration, a linear acceleration, but because it's going around a curve, it has centripetal acceleration. And so the acceleration would not be zero, since it is accelerated. And, hm, the acceleration is inward towards the inside of the curve, hm, because it's counteracting ... The force that causes it accelerating inward is counteracting, hm, momentum, I think, that is moving the car towards the outside of the curve. I think that's why. But I remember it pointing inside from class."

Reasoning processes

Students used a similar pattern of reasoning in approaching all questions. After reading a question, they usually represented the problem by summarizing its salient features. Then they tried to retrieve an appropriate knowledge element that would match the given situation. Finally, they directly applied this element, with little additional processing, to determine their answer.

In some cases a student perceived inconsistencies between the different knowledge elements retrieved to answer a particular question. Some inconsistencies were due to contradictions between everyday experience and knowledge acquired in school. For example, in the case of motion with constant speed along a curve, everyday knowledge suggested zero acceleration due to constant speed, but school knowledge suggested a non-zero acceleration due to a changing direction of velocity. Other

perceived inconsistencies resulted from apparent contradictions between different knowledge elements acquired in physics courses. For example, in the case of the horizontal pendulum, one knowledge element about gravity suggested that the acceleration should be directed downward, but a second knowledge element about circular motion suggested that the acceleration should be directed toward the center.

Students never resolved their perceived inconsistencies, but decided on a particular answer fairly arbitrarily, usually without giving an explicit reason for choosing one knowledge element rather than another. Indeed, because of the fragmented nature of their knowledge, students appear to lack the coherent conceptual framework necessary to determine whether a specific knowledge element is appropriate or not. It is worth noting that students rarely invoked any general definition of acceleration.

Students' Final State: Data and Discussion

The following data and discussion are based on the students' performance after being taught the procedural specification of acceleration. This performance includes students' diagnoses of their own and others' mistakes, and their answers to questions on the posttest.

Diagnostic abilities

Detection of discrepancies. Students reliably detected the discrepancies between two answers -- either between the correct answer and their own wrong answer in the pretest, or between the correct answer and the given hypothetical answer in the other questionnaires. Thus students exhibited the prerequisite skills for diagnosing detected mistakes.

Diagnosis of own mistakes. As mentioned previously, 18 of 30 pretest questions (across all subjects) led to wrong answers requiring a subsequent diagnosis of mistakes. The explicit reasons and warnings given by the students indicate that they diagnosed their own mistakes properly in 15 out of the 18 cases. All students' reasons were judged to be "real" because they were consistent with the students' reasoning previously exhibited in the pretest. For example, a student provided the following diagnosis of his previous answer to the question about the horizontal pendulum: "My answer was perpendicular.... The increasing speed I forgot to taken in (sic) account". Sometimes students cited a reason derived from the procedural specification of acceleration. For example, in diagnosing answers to the question about the oscillating spring at the lowest point, several students said that they should have compared two velocities instead of focusing merely on the single "zero" velocity. In 3 of the 18 cases, the students' diagnoses were wrong, i.e., they gave reasons that did not reflect their previous reasoning in the pretest. (All of these "artificial" reasons can be attributed to thoughtless use of the checklist.)

The diagnostic reasons given by students were described at an appropriate level of generality. They were neither too vaguely general (e.g., no student merely said "I didn't understand the concept acceleration"), nor were they too situation-specific (e.g., no student talked merely about "the acceleration of a horizontal pendulum", but rather spoke about "acceleration in a curved path").

Diagnosis of others' mistakes. Since the 6 students had altogether to diagnose 6 given hypothetical wrong answers, there were a total of 36 wrong answers to be diagnosed. Students provided sensible reasons for 34 of these. In one of the remaining two cases, a student failed to come up with a plausible reason because the right answer was "so obvious" to him; in the other case, a student felt no need to

detect or diagnose a mistake because she herself agreed with the given hypothetical wrong answer. All of the reasons given by the students were plausible, i.e. consistent arguments based on these reasons would lead to the mistakes reflected in the hypothetical answers.

In diagnosing the given hypothetical mistakes, students would commonly attribute to the hypothetical person the same kinds of mistakes which they themselves had committed on the pretest. Indeed, in 11 out of 13 cases, a student's diagnosis of another person's mistakes matched almost verbatim the reasons previously cited for the student's own past mistakes. Sometimes students explicitly recognized such similarities. For example, one student said: "I made that mistake earlier (laughing). Yeah, that's the same problem ... So, yeah, I can see how they would make that mistake."

Checklist. Our checklist, as used in the experiment, was not of much help — and perhaps even harmful. Of the 4 students who had access to the checklist, only 2 actually used it in the diagnosis of their own mistakes. Even these subjects, in more than half of the cases, first cited their own reasons for detected mistakes, and only afterwards tried to match these with the reasons on the checklist. In those cases where the checklist did cue possible reasons, almost half of these were misleading and did not reflect the real reasons. By contrast, the four students, who did not use the checklist for diagnosis of their own mistakes, never mentioned artificial reasons but traced their mistakes to causes consistent with their previous defective reasoning.

In the diagnosis of hypothetical mistakes, almost no differences could be observed between users and nonusers of the checklist. The only exception was the previously mentioned case where one nonuser failed to give a possible reason because he could not imagine one for so obvious an answer.

Accuracy of answers

Recall that the posttest contained 5 questions fundamentally similar to those on the pretest, except that each question was accompanied by a given hypothetical answer. (Only 1 of the 5 answers was correct.) Students were requested to give correct answers to the questions and to suggest reasons for any mistakes found in the hypothetical answers.

In 95% of the posttest questions, the students correctly determined both the magnitude and direction of the acceleration. In only one question did one student fail: in question 3.5 (the ball at the highest point of the arc) the student answered zero acceleration, since "the ball is just sitting there in space for a second". This answer is rooted in a deeper misconception about motion and is not directly related to an understanding of the acceleration concept.

Students' conceptual knowledge

Students' knowledge about acceleration, reflected in performance on the posttest, was markedly different from that exhibited in the pretest. Previously deficient knowledge elements were now invoked in revised form. Some "new" knowledge elements, not evident previously, were also invoked. Furthermore, there were no instances in which a knowledge element was invoked without being actually used as the basis for an answer. We discuss these observations in greater detail below.

Invocation of revised knowledge elements. The revision of an initially deficient knowledge element can be traced across three steps: initial use of the deficient element in the pretest; revision of the element during application of the procedural specification or during diagnosis; and final use of the revised element in diagnosing mistakes or in finding the acceleration. The following quotes illustrate students' revisions of initially deficient knowledge elements.

Quote 4 (Student 4)

Initial use. (See quote 1: Wrong knowledge element "if the velocity is zero, the acceleration is zero".)

Revision. "I was confusing velocity with acceleration. I thought, since the velocity was zero, the acceleration should be zero also. But I didn't consider that..., I was just taking in my one velocity, and to find the acceleration is the change of velocities. So I should have taken two vectors instead of one."

Final use. (The student did not make the same mistake in the similar question 3.5 dealing with a ball at the highest point. Furthermore, the student gave the following reason accounting for someone else's wrong answer.) "The answer is wrong: Acceleration is zero, probably because, since the velocity is zero, ... he didn't take into account that the acceleration is the change of velocity with respect to time."

Quote 5 (Student 6)

Initial use. (See quote 2: Wrong application of knowledge element "if gravity is acting, the acceleration is downward".)

Revision. "From this method (the procedural specification) I understood it should be the other direction than last time. I guess, I was thinking that, hm, the gravity is pulling the bob down, and I guess, I didn't really think about it going in the circular motion.... (Circular motion) produces an acceleration towards the inside of the circle. And, but this is not really directly toward inside because there's also gravitational force, gravity, so this is, hm, the gravity vector, and this is the acceler--, well the centripetal one. And as a result it goes like this direction, which is what I got from this ... procedural specification."

Final use. (Proper performance and correct arguments for all curved paths and all questions involving gravity.)

Quote 6 (Student 5)

Initial use. (See quote 3 reflecting uncertainty about rationale for the inward direction of acceleration in a curved path.)

Revision. (After working through an illustration in the summary sheet, the experimenter asked if the example makes sense.) "Yeah, it makes perfect sense. Yeah, that explains to me, why that goes in. I didn't realize why it did before." (Continuing to explain why the acceleration is exactly perpendicular to the velocity:) "As this angle (between v and v') becomes smaller and smaller, those two (vectors v and v') become closer to be parallel and the vector between two parallel lines would be a perpendicular."

Final use. (The revised knowledge element was subsequently used properly four times without any signs of uncertainty.)

In the pretest, 33 deficient knowledge elements were identified across all students; 20 of these knowledge elements were actually used to answer questions. As a result of the subsequent diagnosis tasks, 16 of these 20 deficient knowledge elements were revised (as indicated by students' verbal statements) and four were never reinvoked. The remaining 13 deficient knowledge elements were invoked in the pretest without actually being used to answer any questions. Of these 13 knowledge elements, 3 became revised, 9 were never invoked in the posttest, and one was reinvoked as the basis for a wrong answer. These data suggest that those knowledge elements which had originally been invoked without being used as the basis for an answer, were much less likely to become revised than those elements which had actually been used.

Emergence of "new" knowledge elements. Some correct new knowledge elements, which had never appeared in the pretest, were invoked in the posttest. For example, in the diagnostic tasks three students invoked the knowledge element "the acceleration can be determined by comparing two vectors". Three other students invoked the element "net acceleration is the vector sum of acceleration along velocity and acceleration perpendicular to velocity", as illustrated by the following quote:

Quote 7 (Student 1)

(During diagnosis task in question 1.4, dealing with the horizontal pendulum:) "Actually it seems that like this is a combination of the ... problem ... (car with constant speed along curve) and the first problem with the car on the line (with increasing speed)."

(Further invocation in question 2.1, particle with increasing speed along circle:) "It does have a linear component because it's changing in speed; at the same time it has a centripetal acceleration due to the rotation."

The data are insufficient to determine whether such new knowledge elements were acquired as a result of learning during the instruction, or whether they had already existed without being invoked in the pretest. However, the second possibility seems unlikely since students tended to invoke any and all possibly relevant knowledge in their attempts to answer the questions in the pretest.

No needless invocation of knowledge elements. In the posttest, unlike in the pretest, no knowledge elements were invoked without actually being used. Instead, all invoked knowledge elements were correct and served a specific purpose: either to determine the correct acceleration (in 8 out of 30 questions), or to diagnose a given hypothetical wrong answer (in 22 out of 24 questions).

Reasoning processes

Students answered each posttest question in the following sequence: They first figured out the right answer (i.e., the correct acceleration), then determined if the given hypothetical answer was correct or wrong, and afterwards gave probable reasons accounting for detected mistakes in the hypothetical answer.

To determine the correct answer, a student used one of the following three approaches, depending on available knowledge elements and on his or her confidence in them. (a) If a student could retrieve a readily available knowledge element which matched the given situation and about which he or she felt certain, the student merely applied this knowledge element as the sole basis for the answer (in 8 out of the 30 questions answered by the students). (b) If a student had a knowledge element that matched the given situation but about which he or she felt uncertain, the student applied it tentatively and then checked the resulting answer by using the procedural specification (in 4 out of the 30 questions). (c) In all other cases the student used the procedural specification as the sole basis for the answer (in 18 out of the 30 questions).

Each student applied the procedural specification in at least three of the five questions of the posttest. Indeed, two students used it for all questions. All students used the procedural specification to answer the two difficult posttest questions (3.3, changing speed on a circle; 3.5, instantaneously zero speed) which were similar to those which had been answered incorrectly by all students in the pretest.

When students used the procedural specification, they did so properly and obtained correct answers — although they did not always implement all steps explicitly and resorted to some shortcuts. For

example, students often determined the change of velocity without explicitly sketching the vector diagram specified in the third step of the procedure.

Students' combined use of knowledge elements and of a general procedural specification is an effective and efficient way of interpreting a concept. Indeed, the invocation of special knowledge elements makes concept interpretation fast and effortless, while the reliance on a procedural specification ensures generality and reliable correctness.

Conclusions and Discussion

Teaching the procedural specification of a scientific concept, and requiring students to compare explicitly such conceptual knowledge with preexisting notions, led to the following results:

(a) The accuracy of answers requiring concept interpretation increased from 40% in the pretest to 95% in the posttest.

(b) Across students, 80% of the deficient knowledge elements used in the pretest were explicitly revised and were afterwards invoked only in corrected form. Furthermore, almost no incorrect or needless knowledge elements were invoked in the posttest.

(c) Students' concept-interpretation processes became reliable and efficient, without apparent interference from prior deficient knowledge or misconceptions. In particular, students invoked and implemented correctly the procedural specification of the concept in order to answer questions about the concept or to check their answers.

(d) Students diagnosed properly the reasons for about 85% of their own previous mistakes. They could also give plausible reasons for 95% of others' concept-interpretation mistakes.

These marked improvements in students' abilities to interpret a difficult scientific concept provide evidence for the validity of the basic principles underlying our instructional design: the teaching of explicit concept-interpretation procedures, the emphasis on the coherence of newly acquired knowledge, and the explicit comparison of such knowledge with preexisting knowledge.

To investigate these instructional principles and their implementation in specific teaching methods, we focussed our attention on the concept of acceleration. However, these principles and teaching methods should be applicable to a far broader range of scientific and mathematical concepts. Thus it would clearly be desirable to investigate such applications to other concepts. In addition, it would be useful to address the following specific questions left unanswered by our work.

What is the long-term effectiveness of learning a coherent procedural specification of a concept? Our study investigated learning outcomes only shortly after the instructional intervention. But what would be the results a few weeks later? We surmise that a generally applicable and readily interpretable procedural concept specification should make students' conceptual knowledge more coherent and stable than the typical novice's reliance on fragmented knowledge elements. However, even initially coherent knowledge might become fragmented and unreliable after some lapse of time.

What specific features of our instructional intervention are necessary and sufficient to lead to reliably correct interpretations of scientific concepts? Our study emphasized both the teaching of a procedural concept interpretation <u>and</u> explicit comparisons between new and preexisting knowledge. But to what extent are both of these features necessary, and what would be the effectiveness of either one by itself?

How might our teaching method be implemented in practical settings? In our investigation each student was taught individually in order to engage the student actively and to provide him or her with immediate feedback. Such individualized instruction might be difficult to achieve in ordinary classroom environments. However, properly programmed computers could be used quite effectively to provide such instruction. Accordingly, we are planning to use computers for our further work on concept learning and teaching, both to facilitate the practical implementation of our teaching methods and to achieve better control of the experimental conditions in our investigations.

Acknowledgments

The work reported in this paper was done while the first author was a visiting scholar in the SESAME Group (the Graduate Group in Science and Mathematics Education) and in the School of Education at the University of California at Berkeley. His stay there was supported by a fellowship from the Swiss National Science Foundation (grant No. 84 GG 08). The work was also partially supported by the Office of Naval Research (contract No. N00014-83-K-0598) and by the National Science Foundation (grant No. MDR-8550332). Our activities benefitted also from discussions with Peter Birns, John Muster, and Philip Reese.

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Appendix: Questions used in the Experiment

Questions in pretest

Prototype question (Question 1.4). A pendulum, consisting of a heavy bob attached to a rod, is released from rest at the point A indicated in the diagram (Figure 3). As the bob descends with increasing speed along a circular arc, it passes the point P where the rod is horizontal. (a) What is the acceleration ot the pendulum bob at the point P? (a) Circle your answer (zero or not zero). (b) If the acceleration is not zero, indicate its direction as precisely as possible by an arrow drawn from the point P.

*** Insert Figure 3 about here ***

Summaries of the other questions. The following paragraphs describe the situations specified in the four other questions. Each question was accompanied by a diagram and requested the same kinds of information (parts a and b) as the preceding prototype question.

Question 1.1: A car is traveling with increasing speed along a straight road to the right.

Question 1.2: A car is traveling with constant speed along a curved road.

Question 1.3: After being thrown vertically up, a ball passes a point P while moving up with decreasing speed.

Question 1.5: A particle, attached to a spring, oscillates vertically up and down. Its speed is instantaneously zero at the lowest point A (where the acceleration is to be found).

Other questions (including those in posttest)

Prototype question (Question 2.1). The following problem was given to a student: "A particle moves around a horizontal circle with increasing speed in a clockwise sense. What is the direction of the acceleration of the particle when it passes the point P on the circle?" [A diagram illustrated this situation.] The student's answer was: "The acceleration at the point P is not zero. Its direction is parallel to the velocity (see arrow in diagram)." (a) Is the answer correct or wrong? (b) If the answer is wrong, give the probable reasons accounting for the student's mistake. (c) Give the correct answer.

Summaries of other questions. The following paragraphs describe the situations specified in the other questions, along with the given hypothetical answers. The structure of all questions was the same as that of the preceding prototype question.

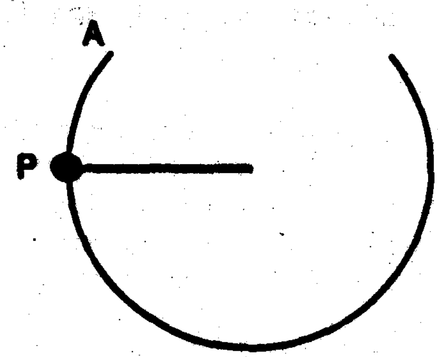

Figure 3. Horizontal position of a descending pendulum.

Question 2.2: Particle attached to oscillating spring; point of interest is where particle moves up with decreasing speed. Given (wrong) answer: Acceleration is not zero; its direction is vertically upward.

Question 2.1: A particle moves around a horizontal circle with increasing speed. Given (wrong) answer: Acceleration is not zero; its direction is along the velocity.

Question 3.1: A particle moves around a horizontal circle with constant speed. Given (wrong) answer: Acceleration is zero.

Question 3.2: After being given an initial push, a sled travels with decreasing speed up along a straight hill inclined relative to the horizontal. Given (correct) answer: Acceleration is not zero; its direction is downward along the hill.

Question 3.3: A car is traveling with decreasing speed along a horizontal curved road. Given (wrong) answer: Acceleration is not zero; its direction is perpendicular to the velocity, pointing inward.

Question 3.4: Particle attached to oscillating spring; point of interest is when particle is moving downward with decreasing speed. Given (wrong) answer: Acceleration is not zero; its direction is vertically downward.

Question 3.5: Ball thrown vertically up, at highest point of its path. Given (wrong) answer: Acceleration is zero.

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